COGNITIVE TUNNELING IN HEAD-UP DISPLAY (HUD) SUPERIMPOSED SYMBOLOGY: EFFECTS OF INFORMATION LOCATION

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ABSTRACT

Cognitive tunneling, the inefficient joint processing of superimposed head-up display (HUD) symbology and the out-the-window scene, was found in an earlier study to occur as a result of locating the HUD symbology near (in visual angle) the outside scene information (Foyle, McCann, Sanford & Schwirzke, 1993). They concluded that cognitive tunneling could be eliminated by placing the HUD symbology away from the out-the-window path which was to be followed. That study, however, had experimental confounds which limit that conclusion. The present study eliminates those confounds by controlling HUD-background contrast, and allowing for the independent assessment of HUD-background complexity and motion. The results indicate that, indeed, cognitive tunneling is eliminated by placing HUD symbology at least 8 deg from the out-the-window scene information.

INTRODUCTION

Superimposed symbology was developed to allow the pilot to view the outside world, while simultaneously viewing aircraft state information. The symbology may be superimposed over a view of the outside world via transparent electronics (as with a head-up display, HUD), on sensor information (as in some helicopter helmet-mounted systems), or on a computer graphics-generated version of the world (as with synthetic vision systems). Operational HUDs use the technique of placing symbology collimated at optical infinity in the pilot's field-of-view. This allows pilots to access both the out-the-window view of the world and onboard aircraft displays in the same region of fixation and accommodation. Without a HUD, pilots must scan their eyes and refocus to view the outside world and the instruments.

Various advantages of HUD over non-HUD designs have been demonstrated (for reviews see Weintraub & Ensing, 1992; and Fadden, Ververs & Wickens, 1998). Early in the development of HUD design, however, a human factors concern surfaced: Fischer, Haines and Price (1980) noted occasions when pilots failed to attend simultaneously to both the HUD symbology information and the outside world information. In their experiment, after landing with the HUD for many trials of practice, an aircraft unexpectedly moved onto the runway from the taxiway. Pilots continued their landing as if the aircraft was not blocking the runway, suggesting that they were not able to adequately monitor the forward visual scene upon which the HUD was superimposed. Extending these results, Wickens and Long (1995) determined that the unexpected nature of the missed information was a determining factor producing these results.

Roscoe (1987) has suggested that these failures occur because HUDs cause pilot's accommodation to move inwards toward the resting dark focus level away from the optimal infinity focus. Roscoe's argument, however, does not explain findings by Brickner (1989) or Foyle, Sanford and McCann (1991) who demonstrated the failure to process simultaneously outside world information and HUD symbology information with a noncollimated graphics display, eliminating any potential focus differences. Both studies found a <u>performance tradeoff</u> between path tracking performance (an out-the-window task) and altitude maintenance performance (a HUD task): Superimposed HUD altitude information (presented in the center of the screen) yielded better altitude maintenance, but with decreased out-the-window path performance. Without HUD digital altitude information, altitude maintenance was poor, but path-following ability was improved.

Brickner (1989) and Foyle, Sanford and McCann (1991) proposed a cognitive/attentional account of this performance tradeoff: Limitations on visual/spatial attention prevented concurrent processing of the HUD symbology and the out-the-window world path information. This has been called "cognitive tunneling", the inefficient joint processing of the superimposed symbology and the out-the-window scene, and demonstrated by the presence of the HUD/world performance tradeoff.

Foyle, McCann, Sanford and Schwirzke (1993) replicated and extended this result. The failure to efficiently process superimposed HUD symbology and out-the-window path information was found only when these two information sources were presented visually near each other, less than 8 deg visual angle apart. When the HUD symbology was more than approximately 8 deg from the out-the-window path information, the performance tradeoff was eliminated, and efficient processing of both HUD and path information was achieved. Foyle et al (1993) proposed that the mitigating effect of visual distance may be because the required eye movements break cognitive tunneling on the HUD symbology (see Weintraub & Ensing, 1992).

The Foyle et al (1993) study, however, had confounds that allow other interpretations. The luminance level of the simulated sky was different from that of the world. (This, of course, is true under actual operating conditions in the real world, but limits the conclusions in an experimental setting.) In that study, when the HUD symbology and the path were separated by 8 deg or more, the HUD symbology was placed above the horizon, against the sky background. The HUD symbology near the path information was superimposed directly over the path, and necessarily placed against the world background. The different luminance levels of sky and world (ground, path pyramids and gridlines) resulted in confounding HUD/background contrasts across HUD locations. For the same reasons, these conditions were confounded by the HUD symbology's background, varying both in motion and visual complexity: The directly superimposed HUD symbology (with the moving path and world gridlines behind it) had a background with higher motion and visual complexity than the HUD symbology conditions placed 8 deg or more from the path (the solid blue sky). Since the performance tradeoff only occurred in the directly superimposed HUD condition, and that condition had a different contrast level and higher visual/motion complexity than the conditions which did not show the tradeoff, it may be that those factors are responsible for the performance tradeoff and not the visual angle distance between the HUD symbology and the path. Additionally, the HUD symbology in that study differed from operational HUD symbology, appearing in a grayed semi-transparent background box, rather than as green luminous symbols over the background scene.

The present study extended the findings of Foyle et al (1993) by eliminating the confounds of HUD background contrast, complexity and motion. HUD background contrast was specifically controlled by matching the luminance levels of the world and the sky. By testing HUD locations placed against both the sky and the world background, at the same visual distance from the path, this factor can be assessed independently from distance.

METHOD

A flight simulation task was used to evaluate the effect of information location on the concurrent processing of superimposed symbology and "out-the-window" information. Thirty-two, 18-30 year old, right-handed male subjects, with normal- or corrected-to-normal acuity and normal color vision were tested. Subjects flew through the virtual environment while simultaneously performing the ground track path task (flying directly over the path markers) and the altitude maintenance task (maintaining 100 ft altitude). The flight simulation was controlled by a Silicon Graphics Indigo2 Impact computer updated at 12-Hz. All display elements (HUD symbology and simulated world) were generated using computer graphics. Images were displayed on a high-resolution 19-inch color monitor placed 65 cm in front of a chair in a sound-attenuated, dark booth. The out-the-window simulation scene was 32.18 deg wide by 24.31 deg high. Subjects controlled the simulation (a simple kinematic control model) with a spring-centered joystick mounted on the right side of the chair. Eight paths were used consisting of 38 pyramids creating a constantly winding path along the ground. The brown pyramids were 24 ft on a side and 6 ft high. The order of the 8 paths was randomized and assigned to each consecutive group of 8 trials, thus yielding random assignment to conditions.

Subjects were instructed to maintain altitude at 100 ft, and to fly over the ground path as closely as possible. On each trial, the first 10-sec of the simulation started at the to-be-maintained 100 ft altitude with no simulated wind disturbances. After the first 10-sec, as the simulated aircraft flew over the first ground path pyramid, simulated horizontal and vertical wind disturbances were initiated. At the fixed 160 kt airspeed, each path required approximately 45 sec to complete. Root mean squared error (RMSE) altitude and RMSE path were measured at 12-Hz quantifying departures from the assigned altitude and paths. RMSE scores for both measures were presented after each trial, and subjects were consistently reminded that both altitude and path maintenance tasks were of equal importance.

The experimental design was a mixed-subjects design. The contrast between the HUD symbology and its background (ground or sky) was a between-subjects factor with two levels (16 subjects in each contrast condition). The within-subjects factor was HUD location, having five levels as described below (four different locations and one absent condition). The five HUD conditions were randomly ordered into blocks of five trials (for each block and subject). Each subject tested in eighteen such blocks, for a total of 90 trials.

HUD digital altitude symbology (bright green digits) was presented in four different screen locations as shown in Figure 1. The four conditions, and their respective distance in visual angle from the path information were: Center (0 deg, directly overlaying the path information); Mid-Upper (7.71 deg, intermediate distance upwards from the path information); Upper (15.43 deg, left corner of the screen, far from the path information); Lower (15.43 deg, left corner of the screen, far from the path information). A control condition ("Absent") in which the HUD information was not presented was also included. At the nominal 100 ft altitude, the three HUD altitude digits spanned 0.62 deg (vertical) by 1.06 deg (horizontal). Pictorial path information (pyramid size and grid) was present in the virtual flight environment during every trial as shown in Figure 1. This pictorial information was the only source of altitude information in the HUD Absent condition.

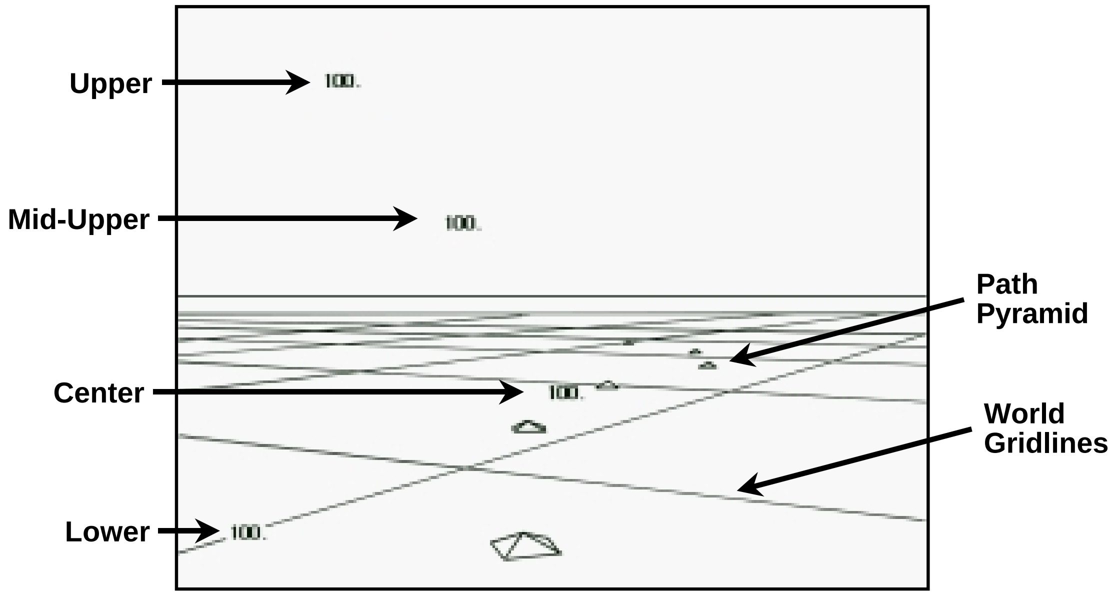

Figure 1. Scale schematic of the four possible HUD locations (no more than one HUD location was presented per trial). The four HUD locations are shown: Lower (15.43 deg); Center (directly superimposed, 0 deg); Mid-Upper (7.71 deg); and, Upper (15.43 deg). A fifth condition (HUD Absent) contained no HUD digital altitude information. World gridlines overlaid on the ground and 6 of the 38 pyramids defining the path are shown.

The HUD symbology contrast ratio, defined as HUD luminance divided by background luminance, was 28.80 (High Contrast) and 7.48 (Low Contrast). HUD symbology luminance in both cases was 67.4 cd/m^2, with background luminances of 2.34 cd/m^2 (High Contrast) and 9.01 cd/m^2 (Low Contrast). In absolute terms, both were fairly high contrast, giving the appearance of a dusk simulation. The luminances of the simulated blue sky and green ground were set perceptually equal by using the method of heterochromatic flicker photometry (see Boff, Kaufman & Thomas, 1986), averaging the results of four subjects (not tested in the present study).

RESULTS

Separate analyses of variance (ANOVAs) were conducted on the RMSE altitude and RMSE path measures. Using a technique used previously (Foyle, McCann, Sanford, & Schwirzke, 1993; Shelden, Foyle, & McCann, 1997) asymptotic performance was determined by the conduct of successive ANOVAs, eliminating increasing numbers of successive initial blocks until no significant effects with Block as a factor were found. As a result of this technique, Blocks 11 - 18 (8 replication blocks of the 5 HUD conditions, for a total of 40 trials) were deemed to be asymptotic, and included in the analysis. Only data from these 40 trials are reported.

For RMSE Altitude (Figure 2 left panel), the results of the 2x5x8 (Contrast x HUD conditions x Block) mixed ANOVA yielded a significant effect of HUD conditions, $F(4,120) = 89.38$, $p<.001$. No other effects were significant. Similarly, for RMSE Path (Figure 2 right panel), the effect of HUD conditions was also the only significant effect, $F(4,120) = 9.89$, $p<.001$. For both dependent measures, altitude and path RMSE, the main effect of Contrast and all interactions were not significant (all $p>.05$). The data patterns for the two contrast conditions were similar, and Figure 2 shows the HUD condition data averaged across the two contrast levels.

Altitude RMSE comparisons. Planned comparisons for altitude RMSE were conducted. All statistical comparisons are averaged across the nonsignificant effect of contrast, and based on all 32 subjects. Additionally, all significance tests reported are 2-tail tests unless noted. The HUD absent condition was significantly worse (higher RMSE error) when compared to all HUD locations (Center, $t(31)=11.77$; Lower, $t(31)=11.42$; Upper, $t(31)=9.99$; Mid-Upper, $t(31)=10.40$; with all $p<.001$). The Center HUD location was statistically better than the Lower location, with $t(31)=2.08$, $p<.05$, and the Mid-Upper location, $t(31)=2.41$, $p<.05$. However, the mean differences are minimal, with means of 20.99, 21.76 and 21.93 for the Center, Lower, and Mid-Upper conditions, respectively. The Center HUD location was not significantly different than the Upper location with $t(31)=1.09$, $p>.25$.

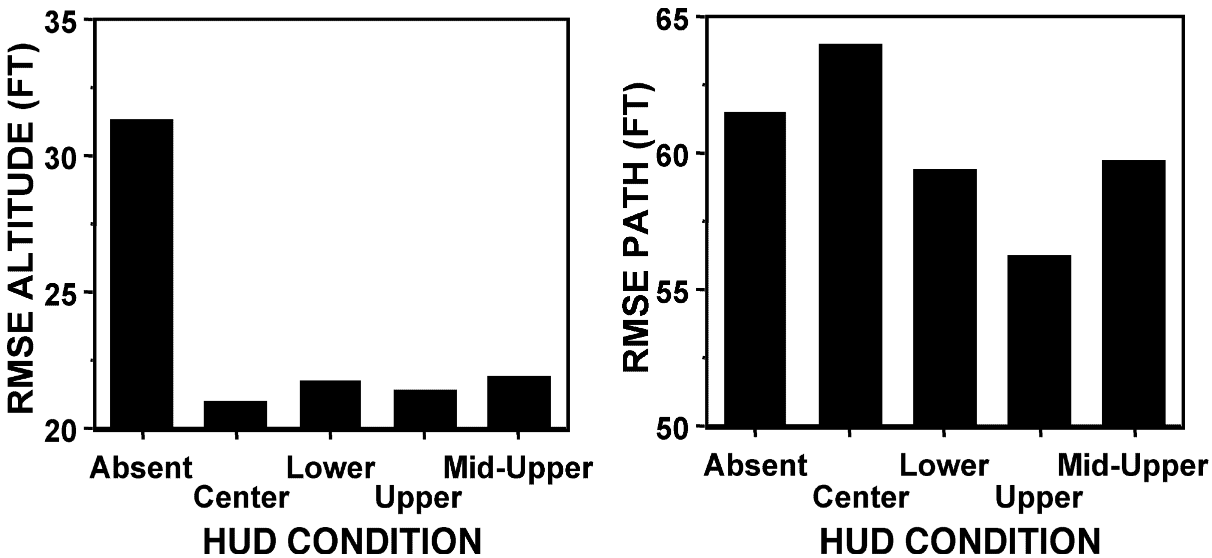

Figure 2. Mean results averaged over the two contrasts tested (N = 32): Effect of HUD condition on Altitude (left panel) and Path RMSE (right panel).

Path RMSE comparisons. For Path RMSE, the Center HUD location was significantly worse than the Absent condition, $t(31)=1.81$, $p<.05$ (for a 1-tail test, $p=.08$ for a 2-tail test). (It should be noted that since this effect was predicted from previous studies, a one-tail significance is justified.) The Center HUD location was also significantly worse than the Lower ($t(31)=3.19$, $p<.01$), Upper ($t(31)=7.08$, $p<.001$), and Mid-Upper ($t(31)=3.85$, $p<.001$) HUD locations. The Upper location was significantly better than all other HUD conditions: Absent ($t(31)=4.33$, $p<.001$); Center (reported above); Lower ($t(31)=3.23$, $p<.01$); and, Mid-Upper ($t(31)=3.49$, $p<.001$).

To summarize the major findings in the above results, there was no effect of Contrast for both Altitude and Path RMSE dependent measures. Not surprisingly, and replicating earlier results, altitude maintenance performance without a HUD digital display (Absent condition) was worse than when HUD information was present, regardless of location. Path maintenance performance with the HUD altitude information displayed in the Center position was worse than when presented in any other location or when the HUD was absent. Additionally, path maintenance performance for all of the non-Center locations was either equal (not significantly different) or better than when no HUD display was available (HUD Absent).

DISCUSSION

First, consider only the data from the Center HUD location and the HUD absent conditions. The results show the HUD/world tradeoff described previously. That is, when HUD altitude information directly overlays the path information, altitude maintenance is improved relative to when no HUD information is available. That improvement in altitude maintenance, however, is accompanied by a corresponding decrease in path maintenance performance.

A different pattern of results was found for HUD locations that were not located in the Center position. For all non-Center HUD locations, altitude maintenance performance was improved relative to when no HUD display was presented. However, the corresponding path maintenance performance is either improved or unchanged relative to when no HUD display is presented. Subsequently, note that these non-Center HUD locations do not show the HUD/world tradeoff seen in the Center location: Improvement in altitude maintenance with a HUD display yields either no change or an improvement in path maintenance performance.

The presence of the HUD/world tradeoff for the Center location replicates the results of several previous experiments (see Foyle, McCann, Sanford, & Schwirzke, 1993 and Shelden, Foyle, & McCann, 1997). The results of the present study also replicate and extend the findings reported in Foyle et al (1993) where the HUD/world tradeoff was only obtained when the HUD location directly overlaid (i.e., the Center condition) the out-the-window path information: When HUD symbology is visually separated from the out-the-window path information (i.e., at least 7.7 deg, as in all other HUD locations), the HUD/world performance tradeoff is eliminated.

The finding that efficient joint processing of the HUD and the out-the-window scene only occurs when an eye movement is required is a somewhat paradoxical finding. The actual cognitive mechanisms by which this occurs are yet to be determined. One possibility is that when HUD symbology is directly superimposed, one may not have conscious access to what is, and what is not, being attended, and this may be the source of the inefficient processing. When HUD symbology is placed away from the out-the-window information, the required eye movement may act as a cue by which one is made aware of this, so that more efficient processing occurs. Future research on this topic is needed to better understand these mechanisms.

The present study extended this finding to exclude two possible confounds in the Foyle et al (1993) study. First, by equating the HUD/background contrast for all HUD locations, HUD symbology contrast was eliminated as a confounding factor. Second, by testing HUD locations that were below the horizon as well as above the horizon, a possible confounding effect of background content and movement was eliminated. Further, generalizability was increased by the use of two contrast levels, and through the use of HUD symbology more similar to that of operational HUDs.

SUMMARY

Previous research (e.g., Foyle et al, 1993) has shown that under certain conditions, the presence of superimposed head-up display symbology containing altitude information improves altitude maintenance performance at the cost of out-the-window path maintenance performance. This implies that, despite the simultaneous visual availability of both altitude and path information, these information sources may not support concurrent cognitive processing (i.e., they may induce cognitive tunneling). In a part-task flight simulation experiment, the influence of the superimposed symbology location on this concurrent processing limitation was evaluated. A superimposed digital altitude (i.e., HUD) indicator was presented in 4 locations, varying from 0 to 15.4 deg from the out-the-window ground path. Additionally, a fifth, control condition, eliminated the digital altitude indicator completely.

When the superimposed altitude symbology was located at least 7.7 deg away from the ground-track path to be followed, path maintenance performance was unaffected. However, when the HUD altitude was directly superimposed over the ground path, this improvement in altitude maintenance produced a corresponding decrease in performance on the ground track task.

These data suggest that visual/spatial attention cannot be directed to both HUD information and out-the-window information simultaneously when directly superimposed. In contrast, the ability to use both the altitude display and the out-the-window path information when the HUD and the world information are not directly superimposed is attributed to the breaking of cognitive tunneling on the HUD, possibly due to required eye movements. Cognitive tunneling is eliminated by placing HUD symbology more than 8 deg from the relevant background.

ACKNOWLEDGMENTS

Funding was supplied by NASA's Aerospace Operation Systems (AOS) R&T Base Program, RTOP 711-41-12. Thanks to George Lawton and Ron Miller of Raytheon ITSS for their technical assistance.

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